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# The Effect of Boron on Active Neutron Measurements: Application for the Mars Science Laboratory Dynamic Albedo of Neutrons Instrument

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**Abstract**—The primary objective of the Dynamic Albedo of Neutrons (DAN) experiment on board the Mars Science Laboratory (MSL) rover Curiosity is to assess the hydrogen content as the rover traverses the Martian surface. Because hydrogen is a light element, it is an efficient moderator for neutrons. The method used to estimate the hydrogen content by the DAN instrument is to measure the thermal neutron count rate emitted from the surface of the soil using a Pulsed Neutron Generator as an activation source coupled with a thermal neutron detector. However, boron has a high cross section for thermal neutron capture and can affect the thermal neutron flux measured by the DAN instrument. Recently, the MSL ChemCam instrument has shown high concentrations of B in the veins of the Murray formation and Yellowknife Bay at concentrations of 100 to 500 ppm. We show that the number of neutrons that are captured in the Martian soil increases with increasing B, resulting in reduced count rates observed by the DAN thermal neutron detector, which can lead to an overestimate of the hydrogen content.

## I. INTRODUCTION

THE primary objective of the Dynamic Albedo of Neutrons (DAN) experiment on-board the Mars Science Laboratory (MSL) rover Curiosity is to assess both hydrogen abundance and burial depth as the rover traverses the Martian surface [1]. DAN uses a Pulsed Neutron Generator (PNG) as a neutron source, coupled with a thermal neutron detector composed of two He-3 proportional counters. One of the He-3 counter is covered with a thin 0.8 mm cadmium foil to absorb thermal neutrons. Because He-3 proportional counters are sensitive to thermal and epithermal neutrons, the difference between the bare counter and the shielded counter is therefore a measure of the thermal neutron count rate. There are two modes in which the DAN instrument can operate: passive and active. When DAN is in active mode, the PNG is turned on and emits pulses of 14.1

MeV neutrons in roughly all directions ( $4\pi$ ). When DAN is in passive mode, the PNG is off so only neutrons produced from galactic cosmic rays and those emitted by the multi-mission radioisotope thermoelectric generator act as neutron source. Neutrons are subsequently moderated in the Martian soil and detected by the DAN thermal neutron detector. The analysis presented in this paper was done for the active mode only.

Because hydrogen is a light element, it is an efficient moderator for neutrons. By measuring thermal neutrons that are moderated and scattered out of the surface of the soil, it is possible to quantify the hydrogen content [1]. However, other elements, such as boron, have a high cross section for thermal neutron capture (Fig. 1) and can affect the thermal neutron flux measured by DAN. In particular, B-10 has a capture cross section of 3840 barns at 0.025 eV and represent 19.8% of the natural elemental abundance.

While Fe is a typical rock forming element, and occurs in consistent amounts throughout the traverse, soluble elements such as B and Cl are concentrated in areas with a lot of water. Hence Cl and B are good tracers of past under-ground water activity. The average rock in Gale crater contains ~20 wt% FeO, with a normal range of ~18-23 wt% FeO, while the range is ~ 0.5-1.5 wt% Cl. Recently, the MSL ChemCam instrument has shown high concentrations of B in the veins of the Murray formation and Yellowknife Bay at concentrations of 100 to 500 ppm [2]. While 500 ppm might be the

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upper limit of B in a particular clay, the fraction of the rock in the lake deposits within Gale crater that could contain B is 50-75%, which shows that the bulk amount of B in the rock is  $\sim 50$ -400 ppm. A new study by Nellessen *et al.* [3] shows the bulk bedrock content could be as high as 500 ppm. Previous studies by Hardgrove *et al.* [4] reported the influence of neutron absorbing element on the thermal neutron count rate measured by DAN and found that the presence of these elements in the surface can influence the interpretation of H content if their abundance is not known and correctly taken into account. Because of the high capture cross section of B-10, the number of neutrons that are captured in the soil increases with increasing B, resulting in reduced count rates observed by the DAN thermal neutron detector.

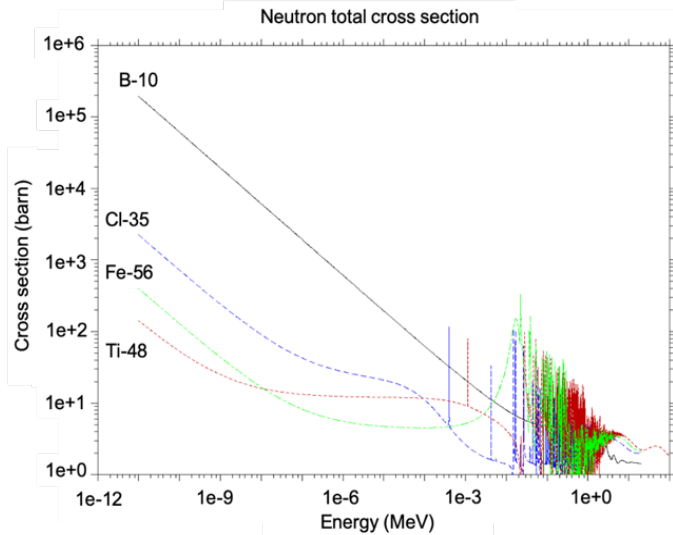


Fig. 1. Total neutron cross sections for Ti-48, Fe-56, Cl-35, and B-10. B-10 has a high cross section for thermal neutron capture hence can affect the thermal neutron flux measured by DAN.

## II. DIE AWAY CURVES

### A. Count rate

Simulations were performed using the MCNP6 code [5] to calculate the neutron count rate in the DAN detectors. Neutrons from the PNG interact with the Martian soil elements through elastic or inelastic scattering and capture. Through elastic and inelastic scattering, the neutrons lose energy and slow down. Once the neutrons are thermal, they can be captured by elements with a high absorption cross-section. Some of the neutrons then come back to the rover and interact with the He-3 detectors. The DAN Detector

and Electronics (DE) has two He-3 proportional counters. One of them is covered with a 0.8 mm cadmium foil. Cadmium absorbs thermal neutrons so the shielded He-3 tube is sensitive to epithermal neutrons only. Epithermal neutrons are defined as neutrons with an energy between 0.4 eV and 1 keV. Thermal neutrons are defined as neutrons with an energy below 0.4 eV. The shielded detector is referred to as the counter of epithermal neutrons (CETN). The other one is referred to as the counter of total neutrons (CTN). The difference between the CTN and CETN counts is therefore a measure of the thermal neutron counts. Each neutron pulse from the PNG lasts about 2  $\mu$ s, and the period between two pulses is 100 ms (Fig. 2). The acquisition with the DAN-DE begins with every pulse of neutrons so that the time of arrival of each neutron in the He-3 detectors is correlated with the start of the PNG neutron pulse. We assumed a rate of  $10^8$  neutrons/s in  $4\pi$ . The acquisition is taken with 64 successive bins that are in a logarithmic scale (Fig. 3). The soil composition that was simulated was derived from the Sebina bedrock geochemistry located in the Murray formation because ChemCam has detected boron in it. The elemental composition of the Sebina bedrock geochemistry can be found in Table 1.

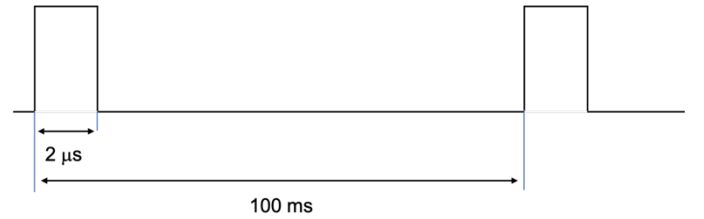


Fig. 2. Time structure of the Pulsed Neutron Generator (PNG).

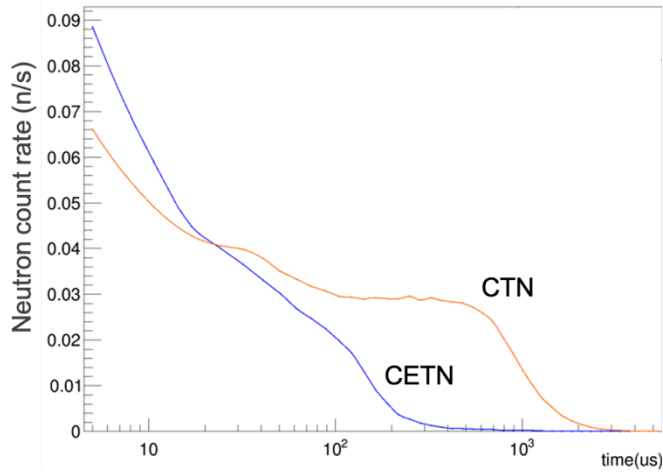


Fig. 3. Neutron count rate as a function of time in the CETN (blue) and the CTN (orange).

TABLE I. COMPOSITION OF THE SOIL

Element	Sebina (element mass fraction %)
Si	30.66
Ti	0.66
Al	4.59
Cr	0.21
Fe	16.93
Mn	0.12
Mg	2.56
Ca	5.09
Na	1.49
K	0.69
P	0.27
S	3.66
Cl	1.06
Br	0.01
Ni	0.10
Zn	0.08
H	0.04
O	43.57

### B. Die Away Curves

Binning the thermal neutron counts allows creating the time profile of the neutron fluxes, also known as neutron die-away curves. To study the effect of boron on the thermal neutron count rate observed in the DAN-DE, the wt% water equivalent hydrogen (WEH) in the composition of the soil varied between 0 and 6 WEH, and the B content varied between 0 and 300 ppm. Fig. 4 shows the neutron die away curves that was simulated as a function of WEH and B. For example, the blue distribution is for a fixed amount of 6 wt% WEH and a varying amount of boron from 0 to 300 ppm (dashed blue curve and solid blue curve, respectively). It shows that as the

amount of boron increases in the soil, the thermal neutron count rate decreases.

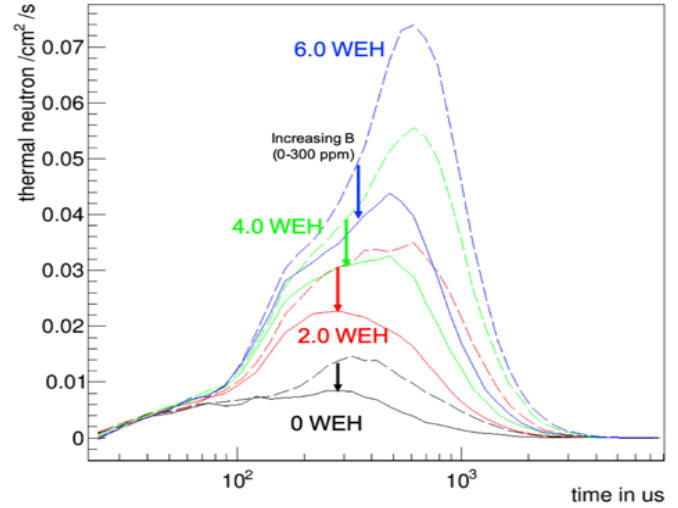


Fig. 4. Simulated neutron die-away curves as a function of water equivalent hydrogen (WEH) and increasing B. Each color represents a fixed WEH, and for each fixed WEH, the B content varies from 0 to 300 ppm. The dotted line for each WEH represents 0 ppm of B. The solid line for each WEH represents 300 ppm of B.

Fig. 5 shows the associated uncertainty as a function of time. To calculate the uncertainties in the measurements, we assumed that the count rate varies in  $1/\sqrt{N}$ , where  $N$  is number of thermal neutron counts in the DAN-DE. The uncertainties show that over time, the measurements in the detector gets better (lower uncertainties). However, because boron has a high absorption cross section, it shows that for a fixed WEH, the uncertainties increases in the measurements due to the presence of boron. To represent the effect of boron in the uncertainties in the measurement, we created a 3D plot of the uncertainties as a function of H and boron for a typical DAN active measurement of 20 minutes (Fig. 6).

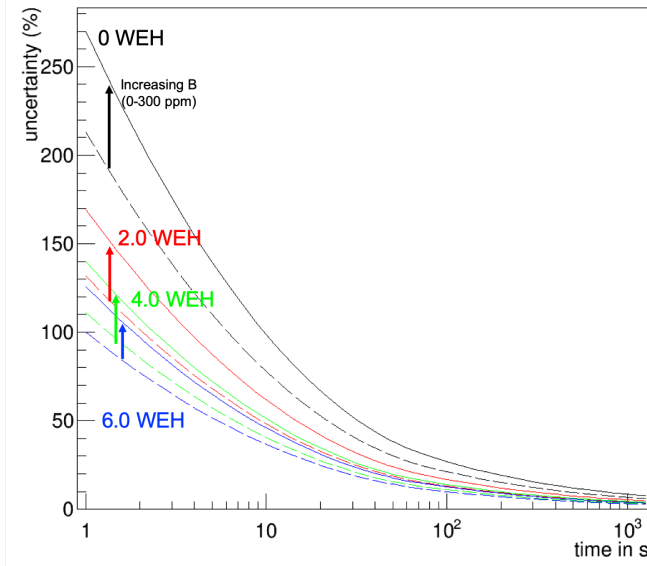


Fig. 5. Uncertainties as a function of water equivalent hydrogen (WEH) and increasing B. Each color represents a fixed WEH, and for each fixed WEH, the B content varies from 0 to 300 ppm. The dotted line for each WEH represents 0 ppm of B. The solid line for each WEH represents 300 ppm of B.

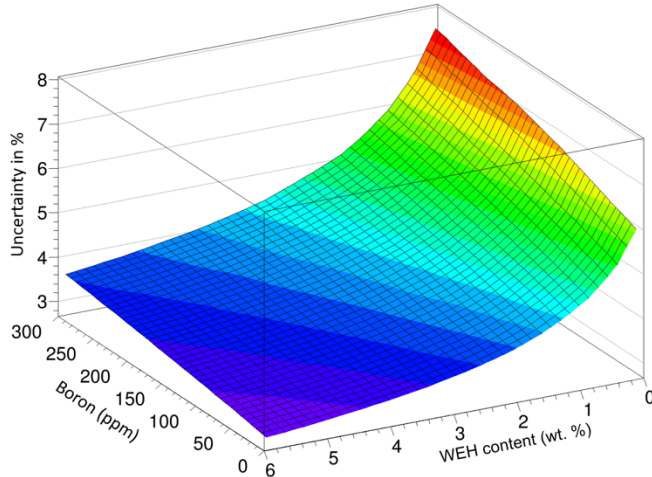


Fig. 6. Uncertainty (% in counts) as a function of WEH and B content after a typical 20-minute DAN active measurement.

### III. CURVE SIMILARITY

The presence of boron can reduce the thermal neutron count rate detected by the DAN-DE and, if not properly accounted for, lead to overestimates of H content. In Fig. 7, we show that the die-away curve for 6 wt%  $H_2O$  with 300 ppm of B is similar to the die-away curve for 2 wt%  $H_2O$  with 40 ppm of B. Hence, in the presence of a high content of B, the WEH content can be interpreted as much lower if the content of B is not known and not taken into account.

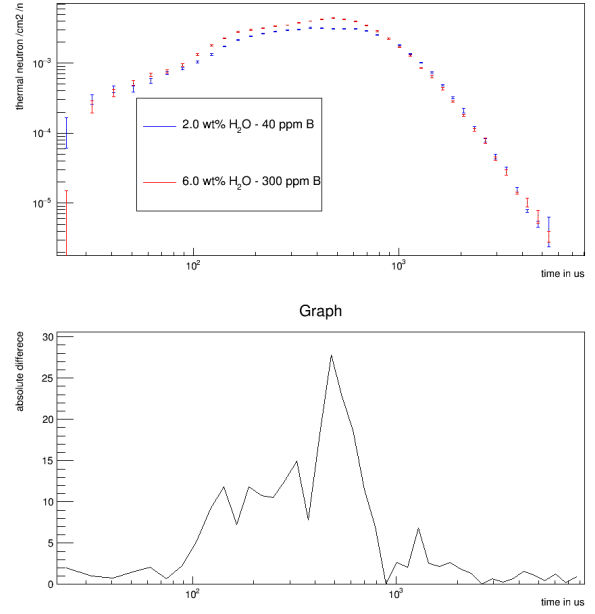


Fig. 7. Example of two similar data sets (6 wt%  $H_2O$  with 300 ppm of B and 2 wt%  $H_2O$  with 40 ppm of B). The calculated sum is low compared to the example shown in Fig. 8, where the two data sets are very different.

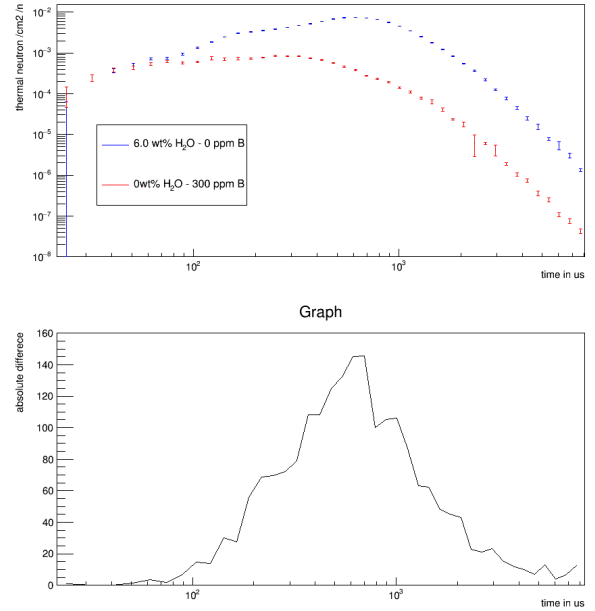


Fig. 8. Example of different data sets (6 wt%  $H_2O$  with 0 ppm of B and 0 wt%  $H_2O$  with 300 ppm of B). The calculated sum increases as the difference increases.

With improved counting statistics from longer measurement times, more accurate quantification of H content in the presence of absorbers could potentially be made based on the shape of the thermal neutron die-away curve but it was not a part of this study.

In order to study the similarity or difference between 2 data sets, we calculated the following sum  $S$ :

$$S = \sum_{i=0}^n \frac{\|N_1 - N_2\|_i}{\sqrt{\sigma_1^2 + \sigma_{2,i}^2}},$$

where  $N_1$  and  $N_2$  are the thermal neutron counts at each time after the pulse,  $i$  is the time after the pulse, and  $\sigma_1$  and  $\sigma_2$  are the errors associated with each count. The sum increases as the difference between two curves increases as shown in Fig. 8. On the contrary, the sum decreases as the similarity between two curves increases, as shown in Fig. 7.

In Fig. 9, we studied the similarity between the data set for 2 wt% H<sub>2</sub>O (top) and 4 wt% H<sub>2</sub>O (bottom) with 0 ppm B and all other data sets that were simulated. Similar calculations were done with the other data sets.

#### IV. CONCLUSION

We showed that the presence of boron can reduce the thermal neutron count rate detected by the DAN detector and, if not properly accounted for, lead to overestimates of H content. We have also developed a method that can be used to study the similarity between two data sets in presence of boron. Other instruments, like ChemCam for example, can detect the presence of boron on the surface of the soil of Mars. However, such instruments can measure only a few hundreds of  $\mu\text{m}$  below the surface and cannot assess the amount of boron in the subsurface of the soil. A solution to this problem would be to use a gamma-ray detector to complement the neutron detector for future instruments that employ neutron die away curve methods. A high-resolution gamma-ray detector would be able to detect the presence of boron through the 478 keV capture gamma-ray line.

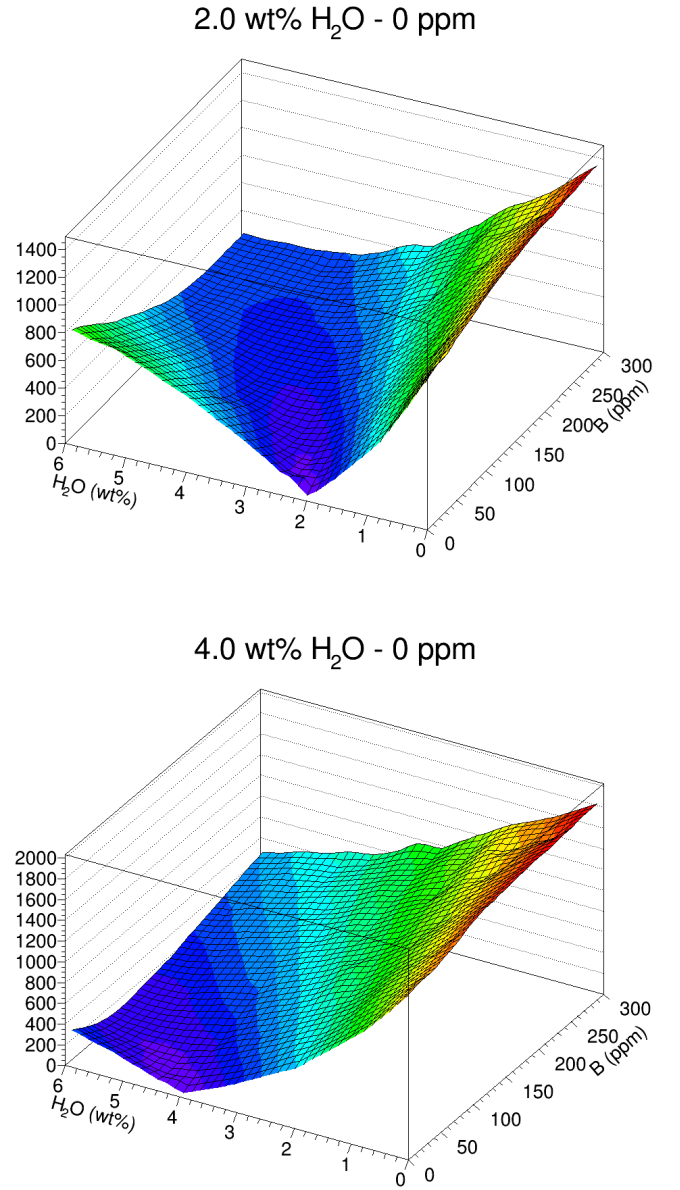


Fig. 9. The sum  $S$  was calculated for the 2 wt% H<sub>2</sub>O and 0 ppm B and all other data sets (top), and for the 4 wt% H<sub>2</sub>O and 0 ppm B and all other data sets (bottom).

#### REFERENCES

- [1] Litvak, M. L., et al. "The dynamic albedo of neutrons (DAN) experiment for NASA's 2009 Mars science laboratory." *Astrobiology* 8.3 (2008): 605-612.
- [2] Gasda, Patrick J., et al. "In situ detection of boron by ChemCam on Mars." *Geophysical Research Letters* 44.17 (2017): 8739-8748.
- [3] Nellessen, M. A., et al. "Adsorption of Boron onto Clay Minerals: Insight into Martian Groundwater Geochemistry." *LPI 2326* (2020): 2694.
- [4] Hardgrove, Craig, J. Moersch, and D. Drake. "Effects of geochemical composition on neutron die-away measurements: Implications for Mars Science Laboratory's Dynamic Albedo of Neutrons experiment." *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment* 659.1 (2011): 442-455.
- [5] Goorley, T., et al. "Initial MCNP6 release overview." *Nuclear Technology* 180.3 (2012): 298-315.